Current Status and Experience of WAMS Implementation in North America

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***Abstract*— The 15 years of successful implementation of Wide-Area Measurement Systems (WAMS) in the WECC power grid have shown significant value of WAMS data in system dynamic modeling and validation, FACTS control validation and pilot implementations of wide area protection schemes. The August 14 2003 blackout in the eastern interconnection of the North America revealed the urgent need for wide-area information acquisition for better power grid operations. The Eastern Interconnection Phasor Project (EIPP) was launched in 2003 to deploy a WAMS system in the eastern interconnection. Development of IEEE C37.118, a standard for phasor data acquisition and transmission, will aid in deployment of phasor measurement systems for WAMS applications. Technologies of Phasor Measurement Units (PMUs) with high precision time synchronization and Phasor Data Concentrators (PDCs) for phasor data aggregation and event recording are key to the success of WAMS implementation. This paper reviews the WAMS development in the North America and presents current and potential WAMS applications including dynamic modeling and validation and wide-area control. Past experience shows a promising future of WAMS in improving power system planning, operation and control. However, there remain challenges to make phasor measurement consistent and to meet both slow and fast data application needs.**

***Index Terms*—Synchronized Phasor Measurement, Wide Area Measurement Systems, Wide Area Protection**

I. Overview of the WECC WAMS

WAMS complements the data acquisition functions of protection relays, fault recorders, and SCADA [1]. Protection relays and fault recorders make local measurements within a substation at very high data rates of thousands of samples per second, while SCADA traditionally provides central measurements of slow power system behavior at data rates in the order of a few seconds. The overall objective of WAMS is to provide dynamic power system measurements in one or the other of two basic forms; raw point on wave data or raw data that has been converted into phasors. Phasor data computation rates range from 10 to 60 phasors per second (systems include Phasor Measurement Units or PMUs) and point on wave data with rates upwards to 30k (systems include Portable Power System Monitors or PPSMs). This paper reports only on the phasor measurement form. Measurements for HVDC controls or other special facilities may be much higher than this.

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Precise synchronization is the key to WAMS performance. Phasor measurements are a technology of choice for the WAMS "backbone," as shown in Figure 1. The phasor network consists of Phasor Measurement Units (**PMU**s) and Phasor Data Concentrators (**PDC**s). A complete WAMS will also accommodate measurements of other types, and it will contain many resources that convert acquired data into useful information.

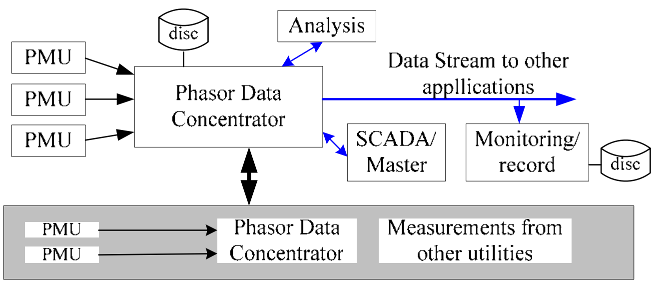

Figure 1 General WAMS structure

The testbed for WAMS development has been the Western Interconnection of the North America power system. Throughout the 1980's the Western System Coordinating Council (**WSCC**) recognized an increasingly acute shortfall in dynamic information [2], and a general plan to remedy this need was formed in 1990 [3]. Technology and infrastructure for the envisioned WAMS were still in the prototype stages, however.

The US Department of Energy (**DOE**) recognized these needs as generic to reliable performance of large power systems. Therefore in 1989, the DOE joined with two federal power utilities - the Bonneville Power Administration (**BPA**) and the Western Area Power Administration (**WAPA**) - in the first large scale WAMS project [4]. In 1994 the Electric Power Research Institute (**EPRI**) initiated the first of several related

WAMS projects [5], and linked their PMU development projects into the overall WAMS effort. The effort also involved many other utilities, plus coordinated development of analysis software [6].

WAMS has close historical linkages to wide area control, and to EPRI's Flexible AC Transmission Systems (**FACTS**) program in particular. BPA and what has since become the Western Electricity Coordinating Council (**WECC**) have some three decades of direct operating experience with FACTS technology or precursors to it. The HVDC modulation system installed at Celilo, Oregon operated for some 12 years, and provided considerable insight into the technical and institutional challenges that confront full-scale use of FACTS control. The WAMS technologies were developed partly in response to those technical challenges, in parallel with research projects on techniques for advanced control plus collaborative enhancements to WECC planning resources [6, 7, and 8].

Progress in the development and use of the WECC WAMS is reported roughly once a year [9, 10, and 11]. By the end of 2004, the WECC WAMS has reached the following size:

- 11 PDC units, operated by 9 data owners.
- 53 integrated PMUs
- 7 stand-alone PMUs
- ~23 PPSM units
- ~10 monitor units of other kinds

The "backbone" system of PMUs and PPSMs continuously provides some 1500 primary signals, about half of them phasors.

The growing WSCC WAMS provided immediate value when the western North American power system experienced massive breakups on July 2 and August 10, 1996 [1, 4, 12, and 13]. The WAMS data was a highly valuable information source for the extensive engineering reviews that followed both events. For the August 10 event, WAMS information was used even more directly where, within minutes of the breakup, WAMS data records were reviewed as a guide to immediate operating decisions in support of system recovery.

So far, accomplishments of the WECC WAMS include the following:

- Maturing of the WAMS technologies for both PMUs and PDCs [14,25,26,27]
- Better insight and modeling for power system dynamics
- High performance resources for direct observation and testing of power system dynamic performance
- Development of a prototype system of WAMS-based wide-area protection known as the BPA's WACS - Wide Area stability & voltage Control System [14].

This paper reviews core WAMS technologies and current status of WAMS applications in the North America. Synchronized phasor measurement and phasor concentration are two basic functions of a WAMS measurement network. WAMS applications include dynamic modeling and validation and wide-area control. New applications are being explored such as state estimation. In the eastern interconnection of the North America, a WAMS-like system is being deployed under the DOE-led project known as the Eastern Interconnection Phasor Project (**EIPP**).

II. WAMS Technologies

A. *Synchronized Phasor Measurement Technology*

The original IEEE Standard 1344-1995 (IEEE Standard for Synchrophasors for Power Systems) established a data format and measurement concepts for synchronized phasor measurement. The new standard IEEE C37.118 will be published in 2005 after 10 more years of WAMS experience and research. Both standardizing efforts are led by Mr. Ken Martin of BPA. The latest IEEE C37.118 improves PMU interoperability with the following three major contributions:

- Refined definition of a "Absolute Phasor" referred to GPS-based and nominal frequency phasors, as well as time-stamping rule;
- Introduction of the TVE (Total Vector Error) to quantify the phasor measurement error;
- Introduction of the PMU compliance test procedure.

Synchronized phasor technology is the preferred basis of a WAMS system. Phasor values are usually estimated from digital samples of the AC waveforms. To make sure that all synchronized phasors have the same reference, the standard defines a synchronized phasor angle as an "instantaneous phase angle relative to a cosine function at nominal system frequency synchronized to UTC. This angle is defined to be 0 degrees when the maximum of the measured sinusoidal waveform occurs at the UTC second rollover (1 pulse per second time signal), and -90 degrees when the positive zero crossing occurs at the UTC second rollover." Figure 2 illustrates the concept showing the nominal 'reference' waveform (dotted line) synchronized with UTC (peaks at 0, T_0, $2T_0$, etc) and the actual waveform (solid line) with growing phase angle (ϕ_i) relative to the reference.

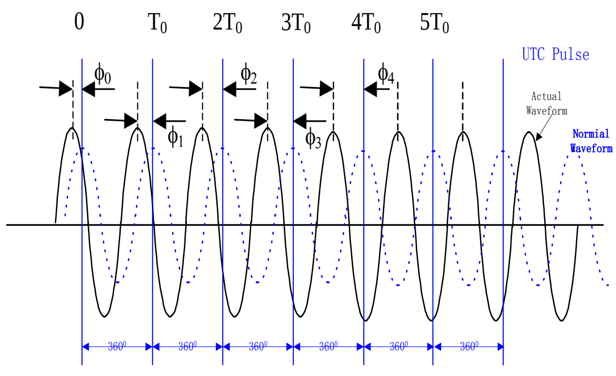

Figure 2 "Absolute Phasor"

The phasor derived from the above definition is an estimated quantity, so we need a way to evaluate the error to make sure all the phasor measurement units in a system have consistent accuracy. IEEE C37.118 introduces the concept of Total Vector Error (**TVE**) to quantify the phasor measurement error, which is defined as:

$$TVE = \sqrt{\frac{(X_r(n) - X_r)^2 + (X_i(n) - X_i)^2}{X_r^{\,2} + X_i^{\,2}}} \qquad (1)$$

where "*r*" and "*i*" denote the real and imaginary parts of a phasor respectively, $X_r(n)$ and $X_i(n)$ are the measured values, given by the measuring device, and X_r and X_i are the theoretical values of the input signal at the instant of time of measurement [16].

Based on the TVE, IEEE C37.118 also recommends the compliance tests which include:

- 10% magnitude step test
- 90° phase step test
- 5Hz frequency step test

In order to accommodate different measurement devices and meet different needs of various applications, IEEE C37.118 further defines the influence quantities and allowable error limits for different compliance levels.

The Standard does not attempt to address all factors that affect PMU response to power system dynamic activity [17]. When applied under field conditions, the TVE will often reflect the presence of signal components other than the fundamental frequency of the power system.

B. Phasor Data Concentrator (PDC) - a Core Component of WAMS

WAMS systems are used for both off-line studies and real-time applications. An important feature of these systems is their ability to provide continuous dynamic measurements that are precisely time synchronized across the power system. With real-time WAMS, the continuous measurements feed out as a data stream which can be applied to on-line applications such as monitoring and control. They can meet real-time control system requirements with time delay less than 1 second (typically 100-200 ms) unlike SCADA which provides only 1-5 second measurement intervals.

The basic functional requirements of a real-time WAMS for discrete control applications include:

- System-wide synchronized phasor data stream broadcasting;
- Maximum and constant response delay in the order of hundreds of milliseconds;
- System-wide dynamic measurement.

Applications that involve large scale continuous control may pose additional requirements to assure operational reliability and to avoid adverse interactions [1, 2, and 18].

To support these requirements, the PDC pioneered by BPA uses a multiple embedded CPU architecture to handle intense communication and data processing. Each PDC may have 4 CPUs, and each CPU with up to 8 PMU inputs using serial or network (Ethernet) connections. The PDC processing delay is very short, typically less than 4 ms.

A PDC collects time-stamped phasor measurements from connected PMUs, adjusts for the differing transmission latency times, accounts for timing and/or transmission errors and integrates all valid reporting PMU measurements into a single composite data packet with a single timestamp. These packets are then streamed via Ethernet or a serial link to subscribing WAMS applications (See Figure 3). The PDC output is a system phasor measurement data stream with the protocol PDCStream via Ethernet or PDCxchng via serial link. Both the protocols were developed by BPA [19]. After the new standard IEEE 37.118 is published, the data stream format defined in the standard will be applicable to PDC output.

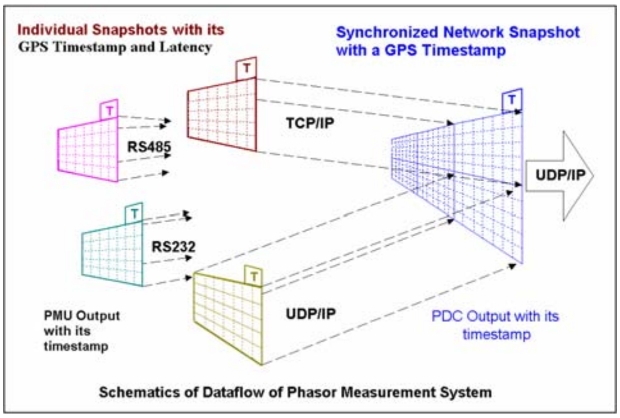

Figure 3 Schematics of PDC's phasor measurement synchronization

A PDC can automatically or manually trigger an event logger when a PMU trigger is detected. Other WAMS applications make continuous or triggered recordings using the continuous data stream. WAMS applications that subscribe to PDC transmission might fit the generic paradigm of Figure 4 [1]. Here sequential WAMS data packets are received and decoded and a custom channel selection is made. This data can then be displayed locally or remotely, archived (all data or just interesting data using one or more limit triggers) for short or long term accessibility. Finally the data can undergo critical time and/or frequency domain analysis as well as be inserted into special control algorithms.

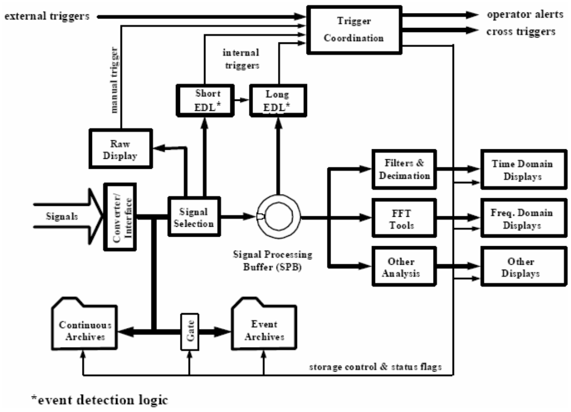

Figure 4 Generic paradigm for an advanced monitor system

A disturbance logging program scans the input data for disturbances detected by a PMU. It records system-wide data in response to a disturbance detected by any PMU. Usually, a few minutes of data are recorded with 55 seconds of pre-disturbance data. If the disturbance continues, the recording continues.

III. Dynamic Modeling and Validation

The WECC WAMS has played a significant role of improving WECC power network dynamic modeling. It recorded valuable dynamic information during the western power system blackouts in 1996. System-wide model validation against recorded system behaviors of 1996 blackouts has been carried out and many model inadequacies were revealed and resolved [13]. Model validation methodology has also been developed to validate models of individual power system components against event recordings [29]. The WECC WAMS has a full set of tools called the Dynamic System Identification (**DSI**) Toolbox to perform system behavior monitoring and system validation [27].

The WAMS-based validation and dynamic performance monitoring methods include:

1. Disturbance analysis employing WAMS data records like those of the 1996 blackouts
2. Ambient noise measurements
    - spectral signatures
    - open-loop/closed-loop spectral comparisons
    - correlation analysis
3. Direct tests with
    - low level noise injections
    - network switching
    - high level pulse inputs

Each of the above methods has its own merits, disadvantages, and technical implications. For comprehensive results, at best cost, a sustained program of direct power system analysis will draw upon all of these in combinations tailored to the circumstances at hand.

The validation procedure, represented in Figure 5, combines model-based analysis with measurement-based analysis[1]. Since the WECC WAMS was put into operation, the WECC has conducted many model validation tests and analyzed many system events including the 1996 two blackout events. Early results of this effort are shown in [6].

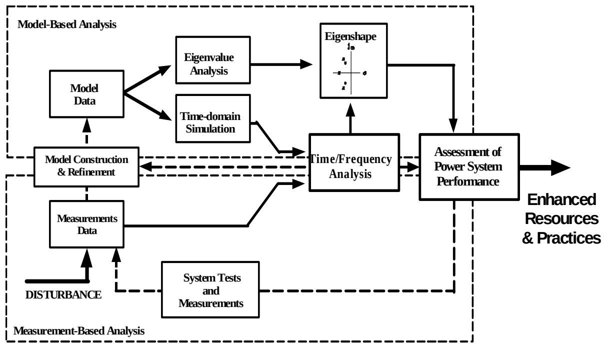

Figure 5 System modeling and performance validation

IV. WAMS-based Wide Area Protection(WAP)

Wide Area Protection (WAP) is a vision [18,27] and could be based on WAMS. In the WECC system, the objectives of WAMS are “enhanced operation and control of the power systems”. The WECC has been working on WAMS-based closed-loop control for years [24]. The current BPA Wide-Area Control System is a response-based discrete control for any system disturbances, which is built on top of the WECC WAMS.

V. Experiences and Lessons

Power system measurements using either conventional transducers (voltage, current, watt, var and frequency) or using PMU measurements require a bandwidth with a minimum range of 0-5 Hz with a response up to 30 Hz with minimal phase distortion. This is also desirable for most WACS applications. It is also important to filter frequencies above the Nyquist sampling limit, particularly at harmonics of 60 Hz. The frequency response should be fairly flat for off-nominal frequencies up to a practical limit for the particular power system. For example, the WECC has run at 0.5 Hz off nominal for periods of time under heavily stressed conditions. Challenges of phasor measurement include:

- To make all the phasor measurements interoperable and consistent; and
- To meet both real time control of fast transient/voltage stability and slow small-signal stability.

To make all the phasor measurements interoperable involves several issues. As data stream with timestamp to every data point, phasor measurement data rates, time-stamping, and communication channel delay will determine whether or not synchronized system phasor data stream be assembled from individual phasor measurement streams from PMUs in a timely manner. The latest C37.118 addresses issues of data rates and time-stamping, but communication channel delay varies with different measurement environments and different communication techniques. Phasor measurement consistency among vendors is even more complicated. Phasor accuracy [13], the size of sampling window, input filtering and phasor calculation algorithms as well as anti-aliasing implementation in every vendor's PMU will definitely have impact on the final analysis of the power system dynamic behaviors [17,35, and 26].

A phasor representation for a power system in steady state is easy to understand and compute accurately. The power system is rarely in its steady state, and phasor measurements must take into account dynamic behavior of the system. The signal will change over the data sampling window used to calculate phasor and frequency, so the values will be some kind of average over that interval. Dynamic components in power systems typically range from less than 1 Hz for inter-area oscillations to above 25 Hz for FACTS controllers. Nyquist criteria requires that the sample rate must be more than twice the highest frequency component, so the phasor estimation rate for a 25 Hz oscillation must be greater than 50 /sec. Necessary filtering is always applied, especially anti-aliasing filters [29]. Those filters are required even before A/D conversion and at any time the original sample rate is reduced. Sometimes it also needs filtering as post-processing the phasor data stream. All these processes make it more complicated to extract power system dynamic signatures from phasor measurements.

VI. Other Development and Ongoing Implementation

In parallel with the WECC WAMS, extensive WAMS facilities are emerging in the North America Eastern Interconnection. Performance of "WAMS East" in recording the massive blackout of August 14, 2003 is reported in [20]. Major expansions to WAMS East are being done under the Eastern Interconnection Phasor Project (**EIPP**), led by US DOE with support from national laboratories and utility companies.

The August 14, 2003 blackout further confirmed the urgent need for wide-area information acquisition for better power grid operations and greatly boosted the EIPP project. The technologies developed in the WECC WAMS are being well leveraged to the eastern system. However, due to the greater diversity of measurement devices and application environments, the EIPP has its own unique issues and the development of the eastern WAMS is not less challenging. Phase I of the EIPP is completed at the end of 2004 with installation of about 30 PMUs and five PDCs, which will use IEEE standards as well as industrial de-facto standard OPC. Among the five PDCs, the one at the Tennessee Valley Authority (TVA) serves as the SuperConcentrator, which is the central data server for the EIPP and where a comprehensive database is maintained for the EIPP. Phase II targets to install 350 PMUs in the Eastern Interconnection. Other EIPP ongoing activities include incorporating wide-area information into state estimation, identifying real-time and off-line phasor applications and developing phasor-data sharing policy and phasor application standards.

Typical applications based on synchronized phasor measurement in the North America also include relaying applications such as adaptive out-of-step relays [21], as well as improving SCADA-based state estimation [22]. The program Advanced Measurement Technologies and Controls, sponsored by US Department of Energy with support from national laboratories has made progress on measurement and control technologies [23].

VII. Conclusion

With the advancements in communication and information technology and the ever increasingly important need of wide-area visibility for power grids, WAMS is being intensively extensively deployed in the North America. The WECC WAMS has, over some the course of some thirty years [1], successfully grown from a sparse collection of local or regional snapshot recorders to an interconnected network providing continuous high quality data across the WECC power grid. Though not fully developed even now, the WECC WAMS has shown significant value of WAMS data in modeling and validation of system dynamics, engineering of high level stability controls, and pilot implementations of wide area protection schemes. In the Eastern Interconnection of the North America, the EIPP project, primarily supported by the US DOE at this stage, has gained acceptance from its member utilities and has made significant progress in deploying a wide-area measurement system in the eastern power grid.

WAMS in the North America with its data acquisition and data management functionality has formed a preliminary data and information platform on which neighboring utilities and control can share information and increase awareness of grid operation status. On top of this data and information platform, an application platform needs to be developed. Current WAMS applications may also need standardized interfaces. The standard 37.118 is the major standardizing efforts, so are the BPA PDC data formats. The EIPP Performance Requirements Task Team is part of the standardizing efforts as well.

Phasor measurement technologies and standards developed during the course of WAMS implementation in the North America would benefit WAMS projects elsewhere. The experience can be well leveraged to WAMS development in other areas through a knowledge sharing and communication channel that has yet to be established.

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BIOGRAPHIES

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John Hauer (F'90) started his engineering career with the General Electric Company in 1961. This was followed by industrial work at Boeing Aerospace, a Ph.D. at the University of Washington, and a faculty position at the University of Alberta. In 1975 he joined the Bonneville Power Administration and began a long involvement with identification, analysis, and control of power system dynamics. In 1994 he stepped down as BPA Principal Engineer for power system dynamics, and assumed technical leadership of the power systems group at the DOE's Pacific Northwest National Laboratory in Richland, Washington. He is a Life Fellow of IEEE.

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